



(12) **United States Patent**
Rothman et al.

(10) **Patent No.:** **US 9,477,813 B2**
(45) **Date of Patent:** ***Oct. 25, 2016**

(54) **METHOD AND DEVICE FOR MULTIMODAL
NEUROLOGICAL EVALUATION**

(71) Applicant: **Brainscope Company, Inc.**, Bethesda,
MD (US)

(72) Inventors: **Neil Rothman**, Baltimore, MD (US);
Arnaud Jacquin, New York, NY (US);
Samanwoy Ghosh Dastidar, North
Potomac, MD (US); **Thomas Radman**,
Takoma Park, MD (US); **Jonathan**
Miller, Washington, DC (US); **William**
Koppes, Landenberg, PA (US); **Leslie**
Prichep, New York, NY (US)

(73) Assignee: **BRAINSCOPE COMPANY, INC.**,
Bethesda, MD (US)

(*) Notice: Subject to any disclaimer, the term of this
patent is extended or adjusted under 35
U.S.C. 154(b) by 0 days.

This patent is subject to a terminal dis-
claimer.

(21) Appl. No.: **14/995,647**

(22) Filed: **Jan. 14, 2016**

(65) **Prior Publication Data**

US 2016/0132654 A1 May 12, 2016

Related U.S. Application Data

(60) Division of application No. 14/295,825, filed on Jun.
14, 2014, now Pat. No. 9,269,046, which is a
continuation-in-part of application No. 13/352,618,
filed on Jan. 18, 2012, now Pat. No. 8,792,974.

(51) **Int. Cl.**

A61B 5/04 (2006.01)
G06F 19/00 (2011.01)
G06N 5/04 (2006.01)
G06N 99/00 (2010.01)
A61B 5/0476 (2006.01)
A61B 5/00 (2006.01)
A61B 5/16 (2006.01)

(52) **U.S. Cl.**

CPC **G06F 19/345** (2013.01); **A61B 5/0476**
(2013.01); **A61B 5/16** (2013.01); **A61B 5/4064**
(2013.01); **A61B 5/7267** (2013.01); **G06N**
5/04 (2013.01); **G06N 99/005** (2013.01)

(58) **Field of Classification Search**

None
See application file for complete search history.

(56) **References Cited**

U.S. PATENT DOCUMENTS

7,251,609 B1 7/2007 McAlindon et al.
2004/0133083 A1 7/2004 Comaniciu et al.
(Continued)

FOREIGN PATENT DOCUMENTS

CN 101583308 A 11/2009
WO 00/10455 A1 3/2000
(Continued)

OTHER PUBLICATIONS

Andrzej et al., "Multimodal Classification: Case Studies," Transac-
tions on Rough Sets V, LNCS 4100: 224-239 (2006).
(Continued)

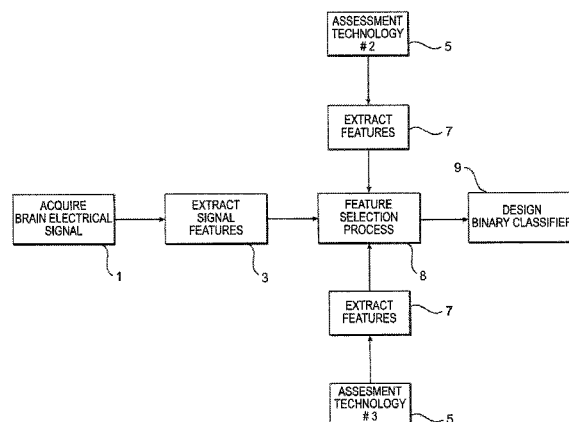
Primary Examiner — Etsub Berhanu

(74) *Attorney, Agent, or Firm* — Finnegan, Henderson,
Farabow, Garrett & Dunner, LLP

(57) **ABSTRACT**

A method of building classifiers for neurological assessment
is described. The method comprises the steps of extracting
quantitative features from a plurality of clinical features, and
selecting a subset of features from the extracted pool of
features to construct binary classifiers. A device for perform-
ing point-of-care neurological assessment using clinical
features is also described.

9 Claims, 3 Drawing Sheets



(56)

References Cited

U.S. PATENT DOCUMENTS

2005/0209785	A1	9/2005	Wells et al.
2007/0032737	A1	2/2007	Causevic et al.
2008/0208073	A1	8/2008	Causevic
2008/0243021	A1	10/2008	Causevic et al.
2009/0220429	A1	9/2009	Johnsen et al.
2009/0264785	A1	10/2009	Causevic et al.
2010/0191139	A1	7/2010	Jacquin et al.
2011/0038515	A1	2/2011	Jacquin et al.
2011/0257267	A1	10/2011	Hadley et al.
2013/0184603	A1	7/2013	Rothman
2014/0081090	A1	3/2014	Picard et al.
2014/0107494	A1	4/2014	Kato et al.

FOREIGN PATENT DOCUMENTS

WO	WO 2008/148894	A1	12/2008
WO	WO 2011/019889	A1	2/2011

WO	WO 2011/115956	A1	9/2011
WO	WO 2014/040175	A1	3/2014

OTHER PUBLICATIONS

International Search Report and Written Opinion for International Application No. PCT/US2013/021387 dated Apr. 3, 2013 (12 pages).

International Search Report and Written Opinion for International Application No. PCT/US2015/032374 dated Aug. 28, 2015 (13 pages).

Quinlan, J.R. "Generating Production Rules From Decision Trees," Paper presented at The Tenth International Joint Conference on Artificial Intelligence, Milan, Aug. 23-28 (pp. 304-307). Netherlands: Morgan Kaufmann (1987).

Wang, H. et al., "Density maximization classification in the lattice machine," Paper presented at The Third International IEEE Conference on Intelligent Systems, Sep. 4-6 (pp. 12-16). New York: IEEE Press (2006).

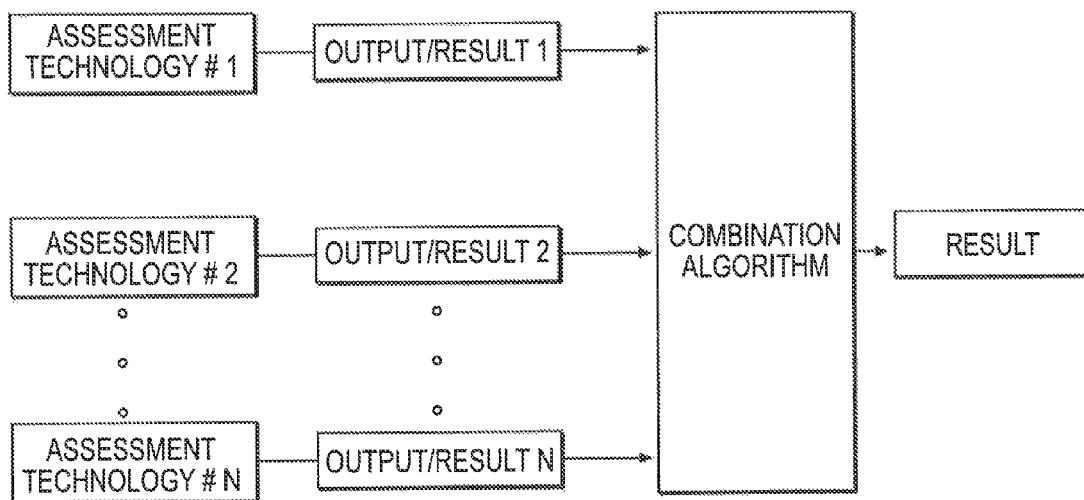


FIG. 1
PRIOR ART

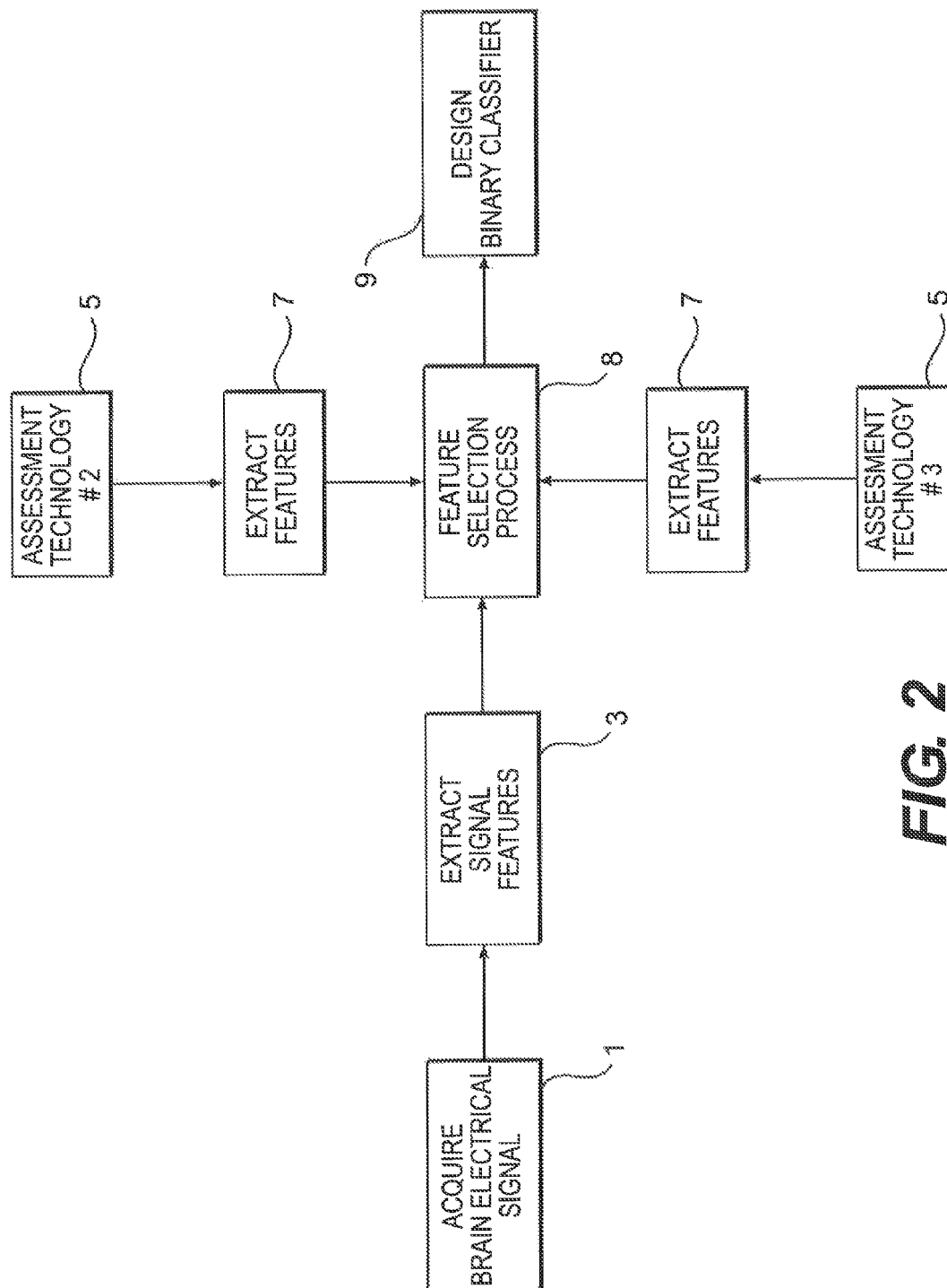


FIG. 2

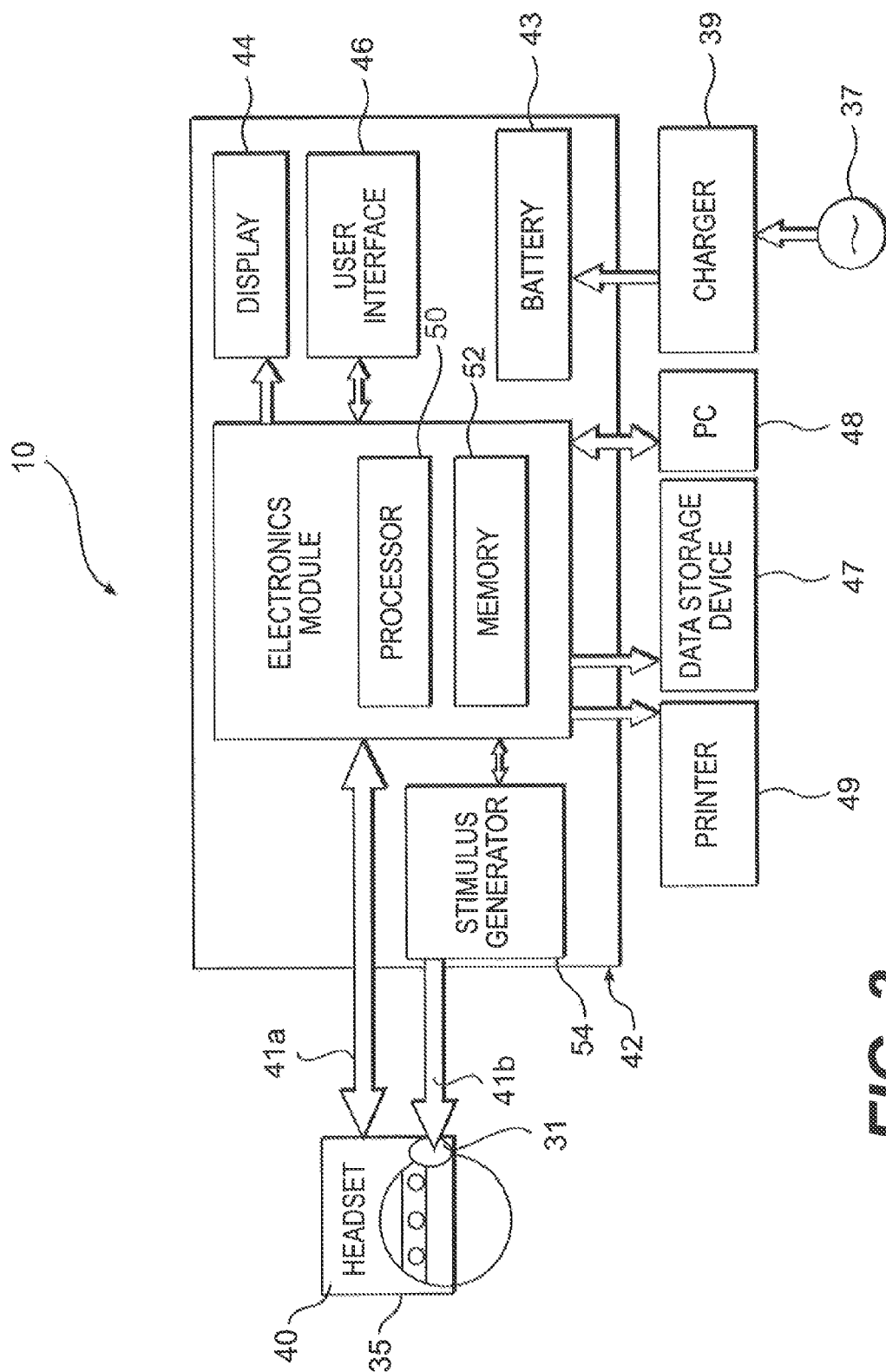


FIG. 3

METHOD AND DEVICE FOR MULTIMODAL NEUROLOGICAL EVALUATION

This application is a divisional of application Ser. No. 14/295,825, filed Jun. 4, 2014, which is a continuation-in-part (CIP) application of U.S. patent application Ser. No. 13/352,618, filed Jan. 18, 2012, which is incorporated herein by reference in its entirety.

The present disclosure relates to the field of neurological assessment, and specifically, to the development of a method and device for combining the results from multiple assessment technologies to provide a multi-dimensional evaluation of a subject's neurological condition.

Currently, objective assessment of brain function is limited to evaluation of a subject's brain electrical activity data collected through EEG (electroencephalography) recording. At a basic level, the brain electrical signals serve as a signature for both normal and abnormal brain function, and an abnormal brain wave pattern can be a strong indication of certain brain pathologies.

Objective assessment of brain electrical signals may be performed using a classifier that provides a mathematical function for mapping (or classifying) a vector of quantitative features extracted from the recorded EEG data into one or more predefined categories. Classifiers are built by forming a training dataset, where each subject is assigned a "label," namely a neurological class based on information provided by doctors and obtained with the help of state-of-the-art diagnostic systems, such as CT scan, MRI, etc. For each subject in the dataset, a large set of quantitative signal attributes or features (computed from the EEG) is also available. The process of building a classifier from a training dataset involves the selection of a subset of features (from the set of all quantitative features), along with the construction of a mathematical function which uses these features as input and which produces as its output an assignment of the subject's data to a specific class. After a classifier is built, it may be used to classify unlabeled data records as belonging to one or the other potential neurological classes. Classification accuracy is then reported using a testing dataset which may or may not overlap with the training set, but for which a priori classification data is also available. The accuracy of the classifier is dependent upon the selection of features that comprise part of the specification of the classifier. Selection of features that contribute most to the classification task ensures the best classification performance.

Although brain electrical activity data provides a valuable means for analyzing brain function, the presence or severity of certain heterogeneous types of brain injury or dysfunction, for example, structural traumatic brain injury (STBI), mild Traumatic Brain Injury (mTBI), cerebrovascular accident/stroke, or neurological diseases such as Parkinson's or Alzheimer's, can be assessed more objectively by combining the results from one or more of a plurality of diagnostic tests. Accordingly, the present disclosure provides a method of expanding the classifier building process to selectively integrate features or outputs from multiple assessment technologies into the feature selection process. The ability to selectively include features from multiple assessment technologies holds the promise of improving classification performance beyond that achieved with features derived only from brain electrical signals.

With regard to neurocognitive assessments in particular, the existing assessment techniques (e.g., New Orleans Criterion (NOC); F.A.S.T. algorithm for early stroke detection; Cincinnati Pre-Hospital Stroke Scale (CPSS), etc.) are typi-

cally used in a pre-hospital or hospital setting for patient triage, in order for a doctor to quickly determine whether a patient may need further tests, such as imaging tests (e.g., CT scan). Facilities to perform these further tests are not always available in an ER, frequently take a long time to perform, and may put the subject at risk of repeated exposure to radiation, e.g. from head CT scans. Generally, the existing clinical assessment techniques have very high sensitivity to disease/injury, but very poor specificity (i.e., high percentage of "false positives"). This means that many subjects are sent for unnecessary, expensive and potentially harmful tests. (see, e.g., "Assessing The Validity Of The Cincinnati Prehospital Stroke Scale And The Medic Prehospital Assessment For Code Stroke In An Urban Emergency Medical Services Agency," J R Studnek, et al., *Prehospital Emergency Care*, July 2013, reporting that the percentage of false positives for the CPSS is 76%.)

The present disclosure, on the other hand, relies on a training database to build a data-driven classification algorithm. Even though the classifier uses some of the same input variables as in the existing neurocognitive assessments and clinical symptoms inventories, the classifier building method of the present disclosure uniquely combines and applies appropriate weights to the various input variables in order to build a classifier with an improved combination of sensitivity and specificity.

Specifically, the present disclosure describes a method of building a classification system for rapid, point-of-care evaluation of a subject's neurological state, wherein the classification system utilizes an optimized set of clinical symptoms and/or results/outputs from neurocognitive assessments to evaluate the subject's neurological condition.

One aspect of the present disclosure is a method of building a classifier for assessment of a subject's neurological condition. The method comprises providing a processing device operatively connected to a memory device storing a reference database of clinical results collected from one or more neurocognitive and/or clinical symptoms assessments performed on a plurality of individuals in the presence or absence of brain abnormalities. The processing device comprises a processor configured to perform the steps of extracting quantitative features from the clinical results, storing the extracted features in a pool of selectable features, selecting a subset of features from the pool of selectable features, constructing a classifier using the subset of features, and determining classification accuracy of the classifier by using it to classify data records having a priori classification information.

Another aspect of the present disclosure is a device for assessing a subject's neurological condition. The device comprises an input device configured to acquire clinical results of one or more neurocognitive and/or clinical symptoms assessments performed on the subject, a processor operatively coupled to the input device, the processor configured to perform the steps of extracting quantitative features from the clinical results of the one or more neurocognitive and/or clinical symptoms assessments performed on the subject, and applying a classifier to perform classification of the subject's neurological condition into one of two or more categories.

It is to be understood that both the foregoing general description and the following detailed description are exemplary and explanatory only and are not restrictive of the invention, as claimed. The terms "EEG signal" and "brain electrical signal" are used interchangeably in this application to mean signals acquired from the brain using neurological electrodes.

The accompanying drawings, which are incorporated in and constitute a part of this specification, illustrate embodiments of the invention and together with the description, serve to explain the principles of the various aspects of the invention.

BRIEF DESCRIPTION OF DRAWINGS

FIG. 1 illustrates a prior art approach to combining results of multiple assessments;

FIG. 2 is a flowchart of a multimodal classifier building process, in accordance with an exemplary embodiment of the present disclosure; and

FIG. 3 illustrates a multimodal neuroassessment apparatus, in accordance with exemplary embodiments of the present disclosure.

DESCRIPTION OF ILLUSTRATIVE EMBODIMENTS

Reference will now be made in detail to certain embodiments consistent with the present disclosure, examples of which are illustrated in the accompanying drawings. Wherever possible, the same reference numbers will be used throughout the drawings to refer to the same or like parts.

Multimodal Classifier Building Method

The present disclosure describes a method for building a classifier for mapping multi-modal assessment data into one or more predefined neurological classes or categories. In an exemplary embodiment, the multiple assessment technologies include various neurophysiological assessments tools, for example, EEG recording, infrared testing to look for blood in the head, clinical testing of biomarkers that indicate brain injury, reaction time testing, eye movement tracking, etc. In another exemplary embodiment, the multiple assessment technologies additionally include neurocognitive assessment (such as, Standardized Assessment of Concussion (SAC), Automated Neurophysiological Assessment Metrics (ANAM), ImPACT, etc.). In another exemplary embodiment, the multiple assessment technologies further include other physiological testing, such as, electrocardiography (ECG or EKG), heart rate variability testing, galvanic skin response testing, biomarker testing, etc. And in yet another exemplary embodiment, the multiple assessment technologies additionally include clinical symptoms, such as, headache, injury above the clavicle, loss of consciousness, etc. The results provided by the multiple assessment technologies are integrated to provide the best classification or assessment performance.

In a conventional approach to combining results of multiple assessments, the outputs of two or more technologies are combined using an algorithm, such as, tree logic, voting methods, or weighted combinations, etc., to provide a combined result, as illustrated in FIG. 1. This is analogous to a physician using the results of multiple tests to diagnose a patient's condition. The result or output from each assessment is provided as an input to the combination algorithm, which is applied to each subject to make an overall classification or assessment of the subject's neurological state. In contrast, the present disclosure describes a method that enables inclusion of results/outputs from multiple technologies as selectable features in the algorithm development process. A significant advantage of the multimodal assessment is the generation of a classifier with an optimized subset of features as input. The integration of multimodal assessment data in the algorithm development process offers a distinct advantage in multiclass classification applications

where the results of certain assessment technologies are not relevant to all of the classes. In such cases, the inclusion of extraneous assessments could potentially distort the overall classification result. The method described in the present disclosure overcomes this disadvantage by enabling the training of the classification algorithm to identify results/features (from all available assessment results) that contribute the most to each classification task.

An exemplary classifier building methodology is illustrated in FIG. 2. The classifier building algorithm, as illustrated in FIG. 2, is executed by a signal processing device comprising a processor. An initial step in the classifier building process is the collection of raw brain electrical signals (step 201). In an exemplary embodiment, a subject's electrical brain activity is recorded using a varying number of non-invasive neurological electrodes located at standardized positions on the scalp and forehead and ear-lobes. In one exemplary embodiment, a subject's brain electrical activity is recorded using an electrode array comprising at least one neurological electrode to be attached to a patient's head to acquire the brain electrical signals. In some embodiments, the electrodes are configured to sense spontaneous brain activity. In other embodiments, the electrodes are configured to sense both spontaneous brain activity as well as evoked potentials generated in response to applied stimuli (e.g. auditory, visual, tactile stimuli, etc.). In exemplary embodiments, the signal/data processor running the classifier building algorithm is configured to implement an artifact detection algorithm to identify data that is contaminated by non-brain-generated artifacts, such as eye movements, electromyographic activity (EMG) produced by muscle tension, spike (impulse), external noise, etc., as well as unusual electrical activity of the brain not part of the estimation of stationary background state. An exemplary artifact detection method is described in U.S. application Ser. No. 13/284,184, which is incorporated herein by reference in its entirety.

The artifact-free data epochs are then processed to extract quantitative signal features (step 3). In an exemplary embodiment, the processor is configured to perform a linear feature extraction algorithm based on Fast Fourier Transform (FFT) and power spectral analysis, according to a method disclosed in commonly-assigned U.S. Pat. Nos. 7,720,530 and 7,904,144, which are incorporated herein by reference in their entirety. In another embodiment, the processor is configured to perform feature extraction based on wavelet transforms, such as Discrete Wavelet Transform (DWT) or Complex Wavelet Transforms (CWT). In yet another embodiment, the processor is configured to perform feature extraction using non-linear signal transform methods, such as wavelet packet transform, according to a method disclosed in commonly-assigned U.S. patent application Ser. No. 12/361,174, which is incorporated herein by reference in its entirety. The features extracted by this method are referred to as Local Discriminant Basis (LDB) features. In another embodiment, diffusion geometric analysis is used to extract non-linear features according to a method disclosed in commonly-assigned U.S. patent application Ser. No. 12/105,439, which is incorporated herein by reference in its entirety. In yet other embodiments, entropy, fractal dimension, and mutual information-based features are also calculated.

In exemplary embodiments, the computed measures per epoch are combined into a single measure of EEG signal per channel and/or a pair of channels and transformed for Gaussianity. Once a Gaussian distribution has been demonstrated and age regression applied, statistical Z transformation is performed to produce Z-scores, which describe the

features. Monopolar features are derived from each electrode, and bipolar features are derived from each pair of electrodes. In some embodiments, multivariate features are derived by combining multiple monopolar or bipolar features. The Z-transform is used to describe the deviations from age expected normal values:

$$Z = \frac{\text{Subject Value} - \text{Norm for Age}}{\text{Standard Deviation for Age}}$$

The Z-scores are calculated using a normative database, which comprises response signals from a large population of subjects believed to be normal. The “normative database” is used for normalization and for age regression. The age-regressed and Z-transformed signal features are stored in another database, referred to as the algorithm development (training) database. The training database is stored in a memory device that is operationally coupled to the processor executing the classifier building algorithm. During assessment of a patient using neuro-assessment apparatus 10 (described in detail later) z-scores are derived using calculations that involve the mean and standard deviation for a particular feature in a normal population. The norming database is used to derive the mean and standard deviation as part of the algorithm development process.

Referring again to FIG. 2, the next step in the algorithm development process is the collection of results from other assessment modalities (step 5) and extraction of quantitative features from the other assessment results (step 7). For example, in one embodiment, the multimodal assessments include reaction time testing. One or more quantitative features are calculated from the results of the reaction time testing. Reaction time test looks at the time it takes a subject to respond to an applied stimuli (visual, auditory, etc.) and compares it to a normative value. Quantitative features are calculated from the results of multiple trials (e.g., the mean and standard deviation of multiple test results). In exemplary embodiments, the features of interest are z-scored and stored in the database for use in the algorithm development process. In some embodiments, the output of the multimodal assessments are represented as quantitative features. For example, in case of features based on clinical symptoms, the output may be a 1 or a 0. Such quantitative features may not be represented as z scores. Similarly, quantitative features are calculated from the output of other assessment technologies (e.g., EKG, galvanic skin reaction testing, etc.) and stored in the algorithm development database. As the database increases in size, the classifier built from the database becomes more robust and performance, as measured by sensitivity and specificity, become more accurate. Therefore, in select embodiments, the classifier building algorithm is adaptive to database evolution, i.e., the classifier is updated periodically as the database grows. In other words, in such embodiments, the classifier becomes more robust and accurate as the database expands.

In an exemplary embodiment, neurocognitive assessment is performed alongside the physiological evaluations. In some embodiments, the neurocognitive assessment is performed using standardized questionnaires for testing the presence or severity of neurocognitive impairment following an injury, such as, the Standardized Assessment of Concussion (SAC), Automated Neurophysiological Assessment Metrics (ANAM), ImPACT, etc. In other embodiments, the neurocognitive assessment is performed using a dynamic questionnaire created from expert neuropsychological

assessment practices. The questionnaire is designed to dynamically adapt to responses given by a subject, i.e., each subject may not be asked exactly the same set of questions. The accuracy of neurocognitive assessment is enhanced by tailoring successive clinical inputs based on responses or values of preceding steps. In yet other embodiments, the neurocognitive assessment of the patient is performed by conversing with the patient. Clinical symptoms based features/results, such as, presence or absence of headache, loss of consciousness (LOC), ability to repeat a short sentence clearly, subject’s age, evidence of physical injury above the clavicle, etc., are collected by physical examination and/or by conversing with the patient. Data from the neurocognitive assessment and clinical symptoms assessment is processed to extract quantitative features (collectively, “clinical features”), for example, reaction time metrics, severity ranking of symptoms (e.g., ranking on a predefined numeric scale), a binary metric indicating presence or absence of a symptom, normalized combinations of symptoms or clinical manifestations, etc., which are entered into the pool of selectable features in the algorithm development database. In case of the dynamic questionnaire, the features that are entered into the database are based on the overall quantitative output from the questionnaire and not based on any specific assessment metrics. In case of standardized questionnaires, the clinical features are associated with their own standardized numerical scale, and the feature values from the scale are entered into the pool of selectable features in the algorithm development database.

In some embodiments, all subjects in the algorithm development database are associated with a full vector of clinical features. In other embodiments, one or more subjects in the database may have one or more missing features. In such embodiments, the missing clinical features are identified and statistical techniques, such as, “missing feature imputation strategies,” are applied to account for the missing features by imputing values for those features based on other available information.

In other embodiments, missing features are handled using a customized “Random Forest” algorithm. This algorithm operates by constructing an ensemble of sub-classifiers. Each sub-classifier is built using a small number of features selected at random from the pool of available features and a small number of subjects selected at random from the pool of available subjects. For any such sub-classifier, a subject is excluded from the building process if that subject does not have all the selected features. This eliminates the problem of missing features for any subject. Subsequently, a final “discriminant” score for each subject is computed as the ratio (expressed as a percentage) of the number of sub-classifiers in which the subject is classified as testing “positive” to the total number of sub-classifiers in the ensemble that were built using the subject. A large number of sub-classifiers is used to ensure that all subjects have representation in the ensemble.

Once quantitative features are extracted from the various assessment technologies (physiological as well as neurocognitive assessments and clinical symptoms) and stored in the algorithm development database, the next step in the algorithm development process is the selection of features that provide the best classification performance (step 8). The weights and constants that define a classification function (such as, Linear Discriminant Function, Quadratic Discriminant Function, etc.) are derived from a set of quantitative features in the algorithm development database. Thus, the design or construction of a classification function targeting any classification task (e.g., “Normal” vs. “Abnormal” brain

function, or “Structural Brain Injury” vs. “No Structural Brain Injury”, etc.) requires selection of a set of features from a large available pool of features in the algorithm development database. The selection of the “best” features results in the “best” classification performance, characterized by, for example, the highest sensitivity/specificity and lowest classification error rates. In order to make the feature selection process more efficient and to ensure higher classification performance, the available pool of features from the multiple assessment modalities must be transformed or reduced to a computationally manageable and neurophysiologically relevant pool of features from which a subset of features for a particular classification task may be selected during classifier construction.

Accordingly, in some exemplary embodiments, the pool of available features in the algorithm development database is reduced to a smaller set of features that contribute directly to a specific classification task. In an exemplary embodiment, a reduced pool of features is created using an “informed data reduction” technique, which relies on the specific downstream application of the classifier, neurophysiology principles and heuristic rules. In exemplary embodiments, the “informed data reduction” method includes several different criteria to facilitate the inclusion of features that most effectively provide separation among the classes. The “informed data reduction” method is described in U.S. application Ser. No. 13/284,184, which is incorporated herein by reference. In some embodiments, the “informed data reduction” method may take into account the reliability/objectivity of the clinical features and/or ease of acquisition and availability (in a clinical environment) of the features to potentially increase the stability and clinical utility of the classifier in downstream applications.

Once all the data reduction criteria are applied, the remaining reduced pool of features is utilized to design a classifier (step 9). In one exemplary embodiment, the classifier is a binary classifier used to classify individual data records as belonging to one of two classes. In another exemplary embodiment, the classifier is a multiclass classifier used to classify data records into more than two classes. In yet another exemplary embodiment, a series of binary classifiers that use either linear or non-linear discriminant functions are used to classify individuals into multiple categories. In some embodiments, $x-1$ discriminant functions are used to separate individual subjects into x classification categories. In an exemplary embodiment, three binary classifiers are designed and implemented for classifying patients into one of four categories related to the extent of brain dysfunction resulting from a traumatic brain injury (TBI), as described in U.S. application Ser. No. 12/857,504, which is incorporated herein by reference.

The construction of a classifier is now described with reference to a binary classifier. In exemplary embodiments, a binary classifier is designed by selecting a specific set of features for each discriminant function based on performance. The search for the “best” features for a binary classification task is performed using a fully-automated system (hereinafter “classifier builder”), implemented as a computer program, the output of which is a Discriminant Function classifier. In exemplary embodiments, identification of the “best” features for a particular classification task is performed by computing multiple classifiers using different combination of features, and evaluating each possible classifier using an “objective function” that is directly related to classification performance. In an exemplary embodiment, the objective function (figure of merit) used by a feature selection algorithm is the area under the Receiver

Operating Characteristics (ROC) curve of a Discriminant Function, which is usually referred to as “Area Under the Curve” (AUC). For a given discriminant-based binary classifier, the ROC curve indicates the sensitivity and specificity that can be expected from the classifier at different values of the classification threshold T . Once a critical value (or threshold) T is selected, the output of the test becomes binary, and sensitivity and specificity for that particular threshold can be calculated. The ROC is the curve through the set of points: $\{(1-\text{specificity}(T), \text{sensitivity}(T))\}$, which is obtained by varying the value of the threshold T in fixed increments between 0 and 100. After the ROC curve is obtained, the area under the ROC curve (AUC) is calculated. AUC is a single number between 0 and 1, which reflects, jointly, the sensitivity and specificity of a binary classifier. Thus, AUC provides a quantitative global measure of achievable classifier performance.

In one exemplary embodiment, the search for the “best” features for a classification task is performed using a feature selection algorithm that is referred to herein as “Simple Feature Picker” (SFP) algorithm. The SFP algorithm selects a first feature by evaluating all features in the database or the reduced pool of features, and selects the feature that provides the best classifier performance. Subsequent features are selected to give the best incremental improvement in classifier performance. In another exemplary embodiment, the SFP algorithm adds multiple features to the classifier at each iteration, calculates AUC of the resulting classifier at each iteration step, and selects the features that provide that greatest improvement in AUC. In some embodiments, the feature selection is performed using Harmony Search or LASSO.

In another exemplary embodiment, feature selection is performed using one or more evolutionary algorithms, for example, a Genetic Algorithm (GA), as described in commonly-owned U.S. application Ser. No. 12/541,272 which is incorporated herein by reference in its entirety. In yet another exemplary embodiment, the search for candidate features is performed using an optimization method, for example, Random Mutation Hill-Climbing (RMHC) method, or Modified Random Mutation Hill Climbing (mRMHC), which can be used in a stand-alone fashion or can be combined with the GA algorithm or SFP algorithm (for example, as a final “local search” to replace one feature by another to improve the final feature subset), as further described in the U.S. application Ser. No. 12/541,272 incorporated herein. In some embodiments, all available features in a database—physiological (e.g., brain electrical signal features, EKG-based features, etc.) and clinical features (collected through neurocognitive assessments) are included in the available pool of features from which the “best” features are selected for building the classifier. In some other embodiments, only the physiological features are included in the available pool of features. In yet other embodiments, only the clinical features are included in the available pool of features. A classification algorithm using only clinical features is referred to hereinafter as “Clinical Feature Based Classification Algorithm.” It has been observed by the inventors of this application that the sensitivity and specificity of the “Clinical Feature Based Classification Algorithm,” particularly for a “structural brain injury” vs. “non-structural brain injury” classification task, is significantly higher than that obtained from existing clinical assessments (e.g., NOC, etc.). The reduction in the number of “false positives” (i.e., increase in specificity) without compromising sensitivity can reduce the number of unnecessary head CT-scans of patients with false positives.

In exemplary embodiments, the classification algorithm may be configured to select which set of features to use, i.e., whether to use physiological features only, use both physiological and clinical features, or use only clinical features. The classifier (discriminant function) to be used may be automatically selected based on the selection of features. In some embodiments, the algorithm may be configured to default to clinical features (i.e., features based on neurocognitive assessments and clinical symptoms), when there is no input of neurophysiological data, for example, when a device implementing the algorithm is not plugged into sensors for collecting biosignals from a subject, or when there is an error in the acquisition of biosignals. In some embodiments, the algorithm may be configured to default to clinical symptoms if there is no time to collect neurocognitive features, or qualified personnel are not available to collect them. In other embodiments, the user may be given an option to select which set of features to use. In yet other embodiments, the algorithm may direct the user to select a particular set of features based on the answers to some initial questions prompted by the algorithm, or the algorithm may itself select a particular set of features based on the answers to the initial questions.

After a classifier is built, classification accuracy is evaluated using a testing dataset comprising pre-labeled data records which are assigned a priori to one of the classification categories. In some embodiments, the testing dataset is separate from the training set. In some other exemplary embodiments, all available data is used for both training and testing of the classifier. In such embodiments, performance of the classifier is evaluated using 10-fold and/or leave-one-out (LOO) cross-validation methods, as described in U.S. application Ser. Nos. 12/857,504, and 13/284,184, which are incorporated herein by reference. After a classifier is built and tested for accuracy, it may be used to classify unlabeled data records (i.e., unknown subjects) as belonging to a particular class.

Portable Device for Field Applications

Another aspect of the present disclosure is an apparatus for performing multimodal neurological triage on a subject. FIG. 3 illustrates a multimodal neuro-assessment apparatus 10, in accordance with exemplary embodiments of the present disclosure. In an exemplary embodiment, the neuro-assessment apparatus 10 is implemented as a portable device for point-of-care applications. The apparatus consists of a headset 40 which may be coupled to a base unit 42, which can be handheld. Headset 40 may include a plurality of electrodes 35 to be attached to a patient's head to acquire brain electrical signals. The electrodes are configured for sensing both spontaneous brain activity as well as evoked potentials generated in response to applied stimuli, such as audio, tactile, or electrical stimuli. In an exemplary embodiment, recording is done using five (active) channels and three reference channels. The electrode array consists of anterior (frontal) electrodes: Fp1, Fp2, F7, F8, AFz (also referred to as Fz') and Fpz (reference electrode) to be attached to a subject's forehead, and electrodes A1 and A2 to be placed on the front or back side of the ear lobes, or on the mastoids, in accordance with the International 10/20 electrode placement system (with the exception of AFz). Other electrode configurations may be utilized as and when required, as would be understood by those of ordinary skill in the art. The use of a limited number of electrodes enable rapid and repeatable placement of the electrodes on a subject, which in turn facilitates efficient, and more accurate, patient assessment. Further, in one embodiment, the electrodes may be positioned on a low-cost, disposable platform,

which can serve as a "one-size-fits-all" sensor. For example, electrodes 35 may be positioned on a head gear that is configured for easy and/or rapid placement on a patient, as further set forth in commonly assigned U.S. patent application Ser. No. 12/059,014, which is incorporated herein by reference in its entirety. Other electrode configurations may be utilized as and when required, as would be understood by those of ordinary skill in the art.

In an exemplary embodiment, the neuro-assessment apparatus 10 utilizes the advantages of auditory evoked potential (AEP) signals to map specific auditory, neurological and psychiatric dysfunctions. In such an embodiment, the headset 40 includes reusable earphone 31 to provide auditory stimuli clicks in either ear. In some embodiments, the auditory evoked potential signal used is auditory brainstem response (ABR). In such embodiments, the auditory stimuli may be delivered at 100 dB Peak-to-Peak Equivalent Sound Pressure Level and at a frequency (rate) of 27 Hz (27 clicks per second) to evoke electrical signals from the brainstem in response to the applied auditory stimuli. Other auditory stimuli may also be used, to evoke mid-latency (20-80 milliseconds) or late auditory responses (>80 milliseconds), including the P300. In another embodiment, headset 40 may include an additional ear phone to deliver white noise in the other ear.

In another exemplary embodiment, the neuro-assessment device 10 utilizes visual evoked potentials (VEP) to evaluate the extent of brain injury or dysfunction. For example, in some embodiments, VEP is used to evaluate post-trauma vision syndrome (PTVS) in patients with traumatic brain injuries (TBI). In one exemplary embodiment, monocular and binocular VEPs are recorded under various stimulus conditions provided by the base unit 42 through display 44. In another exemplary embodiment, headset 40 includes a pair of goggles to provide visual stimuli to patients. In one such embodiment, the goggles are mounted with light emitting diodes (LEDs) to provide flash stimuli to elicit VEPs. In another embodiment, the goggles are mounted with a video monitor to provide pattern stimuli to patients.

In addition to acquiring brain electrical signals, neuro-assessment apparatus 10 is designed to collect the output from other assessment technologies. In one embodiment, the results from other assessment modalities are manually entered by the user through user interface 46. In another embodiment, the results are acquired electronically via wireless or other communication methods. In yet another embodiment, apparatus 10 comprises an accessory device for administering a test and acquiring results. For example, in some embodiments, reaction time testing is performed using an input device, which is independent of user interface 46. The independent input device is used to minimize latency errors, and thereby improve reaction time measurements. Referring back to FIG. 3, display 44 in the base unit 42 comprises a LCD screen, and can further have a user interface 46, which can be a touch screen user interface or a traditional keyboard-type interface. Communication link 41 can act as a multi-channel input/output interface for the headset 40 and the handheld device 42, to facilitate bidirectional communication of signals to and from the processor 50, such that, for example, a command from the user entered through the user interface 46 can start the signal acquisition process of the headset 40. Communication link 41 may include a permanently attached or detachable cable or wire, or may include a wireless transceiver, capable of wirelessly transmitting signals and receiving signals from the headset, or from an external device storing captured signals. In exemplary embodiments, communication link 41 includes

11

two reusable patient interface cables which are designed to plug into the base unit **42** and provide direct communication between the headset **40** and base unit **42**. The first cable is an electrical signal cable **41a**, which is equipped with connectors to attach to the disposable electrodes placed on the patient's scalp. The second cable is the AEP stimulus cable **41b** which provides connection to the earphone **31** for auditory stimulus delivery. In some embodiments, the headset **40** includes analog amplification channels connected to the electrodes, and an analog-to-digital converter (ADC) to digitize the acquired brain electrical signals prior to receipt by the base unit **42**.

In an exemplary embodiment, the brain electrical activity data and the results of the other physiological and neurocognitive assessment technologies are processed by processor **50** in the hand-held base unit **42**. Processor **50** is configured to perform rapid, point-of-care evaluation of a subject's neurological state using instructions stored in memory device **52**. In exemplary embodiments, processor **50** is configured to apply one or more multimodal classifiers to combine the results/outputs from a plurality of assessment technologies and provide a multi-dimensional evaluation of the subject's condition. In one such embodiment, processor **50** is configured to extract quantitative features from the results of the physiological and neurocognitive assessments, and apply one or more discriminant functions to classify an unknown subject as belonging to one of two or more neurological categories.

In illustrative embodiments, memory device **52** contains interactive instructions for using and operating the device to be displayed on screen **44**. The instructions may comprise an interactive feature-rich presentation including a multimedia recording providing audio/video instructions for operating the device, or alternatively simple text, displayed on the screen, illustrating step-by-step instructions for operating and using the device. The inclusion of interactive instructions with the device eliminates the need for extensive user training, allowing for deployment and uses by persons other than medical professional. In some embodiments, the memory **52** may also contain the algorithm development database. In other embodiments, the database may be accessed from a remote storage device via a wireless or a wired connection. Further, in some exemplary embodiments, memory **52** includes a dynamic software designed to lead a medical personnel with minimal training through a step-by-step assessment of a subject. The software is designed to present assessment questions to the user based on responses provided by the subject to prior questions. The questions are designed to guide the user through the various available assessment tools.

The classification result obtained from processor **50** is displayed on the display screen **44**, or saved in external memory or data storage device **47**, or displayed on a PC **48** connected to the base unit **42**. In one embodiment, base unit **42** contains a wireless transceiver to transmit the results wirelessly to a remote network or PC **48**, or the external memory **47** to store the results. In some embodiments, the neuro-assessment apparatus **10** can also transmit data to another mobile or stationary device to facilitate more complex data processing or analysis. For example, the neuro-assessment device, operating in conjunction with PC **48**, can send data to be further processed by the computer. In another embodiment, the results can be transmitted wirelessly or via a cable to a printer **49** that prints the results. Base unit **42** can also contain an internal rechargeable battery **43** that can be charged during or in between uses by battery charger **39** connected to an AC outlet **37**. The battery can also be

12

charged wirelessly through electromagnetic coupling by methods known in the prior art. In some embodiments, the base unit **42** further includes a stimulus generator **54** for applying stimuli to the subject for AEP measurement, or for reaction time measurement. In some embodiments, the stimulus generator is included in the headset **40**.

In another exemplary embodiment, user interface **46** receives and displays usage setting information, such as the name, age and/or other statistics pertaining to the patient. In some embodiments, the user interface **46** comprises a touchscreen for entering the user input. A virtual keypad may be provided on the touchscreen interface for input of patient record.

The neuro-assessment apparatus **10** is designed for near-patient testing in emergency rooms, ambulatory setting, and other field applications. The neuro-assessment device is intended to be used in conjunction with CT scan, MRI or other imaging studies to provide complementary or corroborative information about a patient's neurological condition. The key objective of point-of-care neuro-assessment is to provide fast results indicating the severity of a patient's neurological condition, so that appropriate treatment can be quickly provided, leading to an improved overall clinical outcome. For example, neuro-assessment device **10** may be used by an EMT, ER nurse, or any other medical professional during an initial patient processing in the ER or ambulatory setting, which will assist in identifying the patients with emergency neurological conditions. It will also help ER physicians in corroborating an immediate course of action, prioritizing patients for imaging, or determining if immediate referral to a neurologist or neurosurgeon is required. This in turn will also enable ER personnel to optimize the utilization of resources (e.g., physicians' time, use of imaging tests, neuro consults, etc.) in order to provide safe and immediate care to all patients.

In addition, neuro-assessment device **10** is designed to be field-portable, that is, it can be used in locations far removed from a full-service clinic—for example, in remote battlefield situations distant from military healthcare systems, during sporting events for identifying if an injured athlete should be transported for emergency treatment, at a scene of mass casualty in order to identify patients who need critical attention and immediate transport to the hospital, or at any other remote location where there is limited access to well-trained medical technicians. In exemplary embodiments, the "Clinical Feature Based Classification Algorithm" is implemented as an application or "app" on a device (e.g., computer, tablet, smart phone, etc.) without requiring any dedicated hardware or data acquisition system. In such embodiments, the device serves as neuro-assessment device **10**. The processor and memory of the device serves as processor **50** and memory **52**, respectively, of neuro-assessment device **10**. Further, in such embodiments, the values of the clinical features can be entered by a user (clinician or the subject himself) using user interface **46** (e.g., via a GUI) provided with the device.

Other embodiments of the invention will be apparent to those skilled in the art from consideration of the specification and practice of the invention disclosed herein. It is intended that the specification and examples be considered as exemplary only, with a true scope and spirit of the invention being indicated by the following claims.

The invention claimed is:

1. A device for multimodal assessment of a subject's neurological condition, the device comprising:

13

an input device configured to acquire clinical results of two or more neurocognitive and/or clinical symptoms assessment performed on the subject;

a processor operatively coupled to the input device, the processor configured to perform the steps of:

extracting quantitative features from the clinical results of the two or more neurocognitive and/or clinical symptoms assessments performed on the subject; and

applying a multimodal classifier with the extracted quantitative features to perform multimodal classification of the subject's neurological condition into one of two or more categories, wherein the multimodal classifier is pre-developed and pre-trained using selectable features from a training dataset comprising assessment data from two or more different types of neurocognitive and/or clinical symptoms assessments performed on a plurality of individuals in the presence or absence of brain abnormalities; and

a display screen to display a result of the multimodal classification of the subject's neurological condition.

2. The device of claim 1, wherein the input device comprises a user interface for entering the clinical results of the two or more neurocognitive and/or clinical symptoms assessments.

14

3. The device of claim 1, wherein the input device comprises a wireless connection for wirelessly acquiring the clinical results of the two or more neurocognitive and/or clinical symptoms assessments.

4. The device of claim 1, further comprising a memory device for storing interactive instructions for using and operating the device.

5. The device of claim 4, wherein the memory device stores a dynamic questionnaire that provides step-by-step instructions for performing the two or more neurocognitive and/or clinical symptoms assessments.

6. The device of claim 1, further comprising a monitor for providing visual stimuli to the subject to elicit visual evoked potentials.

7. The device of claim 1, further comprising a pair of goggles for providing visual stimuli to the subject to elicit visual evoked potentials.

8. The device of claim 1, further comprising one or more earphones to provide auditory stimuli to the subject to elicit auditory evoked potentials.

9. The device of claim 1, further configured to transmit data to another mobile or stationary device to facilitate more complex data processing or analysis.

* * * * *